Diffraction Effects on a Dual External Cavity Tunable Laser ECTL Source

Ahmed Fawzy[1], **Osama Elghandour**[2], **and Hesham F. A. Hamed**[1]

[1]Electrical Engineering Department, Faculty of Engineering, Minia University, Minia, Egypt
[2]Electronics and Communications Engineering Department, Faculty of Engineering
Helwan University, Cairo, Egypt

Abstract— Diffraction and truncation effects are the important effects that appear due to miniaturization of the external cavity tunable laser source ECTL. So in this paper presents the diffraction effects on the performance of an dual external cavity tunable laser source, whose external cavities are constructed by micro electro mechanical systems (MEMS). One of the main problems in these structures is the optical diffraction as the emitting surface of the laser diode is usually quite limited in the transverse directions. The emitted beam diffracts rapidly in the air and only a small amount of light is coupled back to the source that usually limits the tuning range of the source. The simulation results have shown that dual external cavity has large tuning range than single external cavity by using new expression. It is shown that multiple reflection has significant effect in our model. To get a better engineering for the dual ECTL dimensions, diffraction and Truncation effects must be taken into account.

1. INTRODUCTION

Tunable lasers have wide applications in communication especially in wave length division multiplexing (WDM), sensing application and measurements [1–3]. There are three specifications must achieved in tunable laser to be applicable in modern applications. The specification are the wide tuning range, high tuning speed and miniaturized device dimensions [3–8]. These three specifications can be achieved using the Micro Electro Mechanical System (MEMS) technology [2, 3].

There are many features. That make MEMS technology preferred in fabrication of micromechanical structures such as self aligned, fast response in moving, high accuracy and enhanced mechanical stability [3, 9, 10]. The MEMS technology can add a lot of features like the small size, low weight as well as high tuning speed. For this purpose, MEMS based tunable laser structures have been proposed and tested in the literature using different structures [2, 3]. These structures are mainly based on one external cavity semiconductor laser in which the external cavity is formed by a moving MEMS mirror but suffer from lower tuning range. To increase the tuning range grating must be used in the structures such as Littrow or Littman but also these structures suffer from large size [2–4]. So in this paper dual external cavities is used to enhance tuning range than single external cavity and also miniaturize size than Littrow and Littman [11, 12]. The configuration consists of two cavities one reflective movable mirror element was placed close to the original cavity to form first cavity and the second mirror is transparent mirror. It was placed far from original cavity to form the second cavity. One way to fabricate this moving mirror as well as its actuator is to use the Deep Reactive Ion Etching DRIE technology on SOI wafer [2, 9, 10]. The objective of this paper is to study the diffraction in the MEMS based dual external cavity tunable laser source and to prove that the tuning range is increased in case of dual external cavity. Simulation of the optical field propagation in the structure is verified by accurate theoretical model [13]. In the model each external cavity can be represented by using effective reflection coefficient. The model is based on the plane wave expansion method. The calculation of tuning range through an effective phase perturbation technique is done by using effective reflection coefficient. In this technique phase oscillation condition for the laser oscillator is changed due to perturbation that come from external cavity phase. Based on that, the new resonance frequency (emission wavelength) is then calculated.

2. SYSTEM MODEL

MEMS dual external cavity tunable laser is shown in Fig. 1 with two external mirrors assumed to have finite dimensions limited by the technological capabilities of the DRIE technology. In our formulation we assume that L is the primary cavity's length (containing the active medium), L_{ext1} is the length of the first external cavity, L_{ext2} is the length of the second external cavity, r_1 and r_2 are the reflectivities of the facets forming the original cavity, r_{ext1} is the reflectivity of the first

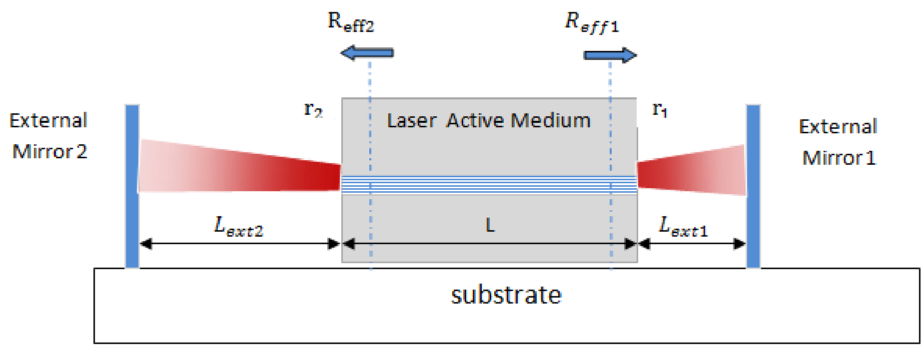

Figure 1: Schematic diagram of the studied dual ECTL source.

external mirror and r_{ext2} is the reflectivity of the second external mirror. The external reflector can be combined with the facet of the primary cavity yielding an effective reflectivity r_{eff} [12, 14] that can be expressed as:

$$r_{\mathit{eff}1}(\nu) = r_1 - \frac{1-R_1}{r_1}\sum_{n=1}^{\infty}\left(-r_1 r_{\text{ext1}} e^{2i\theta_{r1}}\right)^n \tag{1}$$

$$r_{\mathit{eff}1}(\nu) = |r_{\mathit{eff}1}| \exp\left(-j\emptyset r1\right) \tag{2}$$

$$r_{\mathit{eff}2}(\nu) = r_2 - \frac{1-R_2}{r_2}\sum_{n=1}^{\infty}\left(-r_2 r_{\text{ext2}} e^{2i\theta_{r2}}\right)^n \tag{3}$$

$$r_{\mathit{eff}2}(\nu) = |r_{\mathit{eff}2}| \exp\left(-j\emptyset r2\right) \tag{4}$$

$r_{\mathit{eff}1}$, $r_{\mathit{eff}2}$, $\emptyset r1$, $\emptyset r2$ represent the amplitude and phase of effective reflectivity of first external cavity and second external cavity respectively, R_1, R_2 is the power reflectivity of the two facets of the primary cavity and θ_r represents the phase term corresponding to each external cavity length at wavelength λ. In the dual external cavity tunable laser the external mirror of the second cavity is actually transparent so in this paper we make classification for the coupled feedback based on the first external mirror only. In case of weak feedback, $r_{\text{ext1}} \ll r_1$, so we can neglect multiple reflection and can substitute in Equation (1) by $n = 1$. In case of strong feedback, $r_{\text{ext1}} \gg r_1$, multiple reflections will affect the total amplitude and phase of effective reflectivity. From the previous work the best external cavity reflectivity is for the external cavity mirror to match the reflectivity of both internal mirror of the primary cavity [12]. As the optical frequency is mainly determined from the phase condition in the round trip of the laser cavity, we calculate the change in the round trip phase due to the existence of the external cavities. When the phase takes values of multiples of 2π, the oscillation condition can be satisfied again and a laser longitudinal mode oscillates. This change in the phase can be calculated from Equation (5) [15]:

$$\Delta\emptyset_l = 2\pi\tau_l\left(\nu - \nu_{th}\right) + \emptyset_r - \left[\alpha\left[\ln\frac{1}{|r_{\mathit{eff}1}|\,|r_{\mathit{eff}2}|} - \ln\frac{1}{|r_1|\,|r_2|}\right]\right] \tag{5}$$

where τ_l is the round trip time delay of the optical beam inside the primary laser cavity, $\emptyset_r$ represent the total phase of effective reflectivity due to two cavities, ν is the new oscillation frequency and ν_{th} is the oscillation frequency before using an external cavities and α is the linewidth enhancement factor in the semiconductor material. From this relation, we can find a new formula for the frequency shift of the laser emission that result due to using dual cavities as follows:

$$\text{Freq shift} = v - v_{th} = \frac{\left[\alpha\left[\ln\frac{1}{|r_{\mathit{eff}1}||r_{\mathit{eff}2}|} - \ln\frac{1}{|r_1|*(|r_2|)}\right] - \emptyset r\right]}{2\pi\tau_l} \tag{6}$$

This expression for the frequency shift is valid for both weak and strong feedback reflections. It can thus be used to study the effect of the diffraction on the frequency shift and hence on the resonance frequency of the laser.

To calculate this frequency shift, it is required to evaluate both the amplitude and phase of the reflected beam after travelling in the external cavity. For this purpose we use the plane wave expansion method. In this technique, the output beam from the active medium is analyzed as a superposition of plane waves. Each plane wave has its amplitude and phase determined from the field profile using the Fast Fourier Transform FFT technique. Propagation in the external cavity is represented for each plane wave component as a multiplication by a free space transfer function [16]. The total field composed of all the plan waves is then constructed again at the surface of the external reflector using the inverse Fourier transform IFFT to return to spatial domain. When the external mirror has finite dimensions, part of beam is reflected by mirror reflectivity and another part doesn't reflect due to finite mirror size and thus we have a truncated beam. The part that reflected from mirror is modulated by the shape of mirror. The reflected beam is then transformed again to the spectral domain and propagated in the free space as before. When arriving back to the laser diode surface, the beam is returned back to the spatial domain using the IFFT and its coupling to the cavity is calculated using the overlap integral with the cavity mode [6].

For the infinite mirror, the tuning range of dual external cavity tunable laser is higher than single external cavity tunable laser as shown in Figure 2. In our calculation we assume that the laser output is an elliptical Gaussian beam with a spot size of about 3.5 µm in the x direction and 1 µm in the y direction [16–19]. The field distribution at the output of the laser diode can thus be expressed as

$$E(x,y) = E_m e^{\frac{-X^2}{W_{0x}^2} + \frac{-Y^2}{W_{0y}^2}} \tag{7}$$

where E_m is the field amplitude at the center of the beam, w_{ox} is the spot size in the x direction and w_{oy} is the spot size in the y direction and the beam phase front is assumed at the emitting edge of the laser diode surface. The laser source is emitting at the wavelength of 1550 nm. Because of the spot diffraction and in the absence of any focusing element, the external cavity length needs to be very short to maintain feedback efficiency acceptable. For a mirror with finite height, the power loss is more important as part of it is due to the diffraction effect and another part is due to truncation caused by the finite mirror height.

3. RESULTS

For weak feedback with $r_{\text{ext1}} \ll r_1$, in dual configuration, we assume only one round trip in the calculation. For an external mirror with high reflection coefficient, the optical beam intensity, after

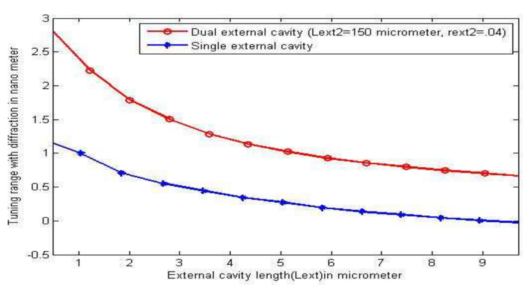

Figure 2: Tuning range of two different configurations as a function of the external mirror position.

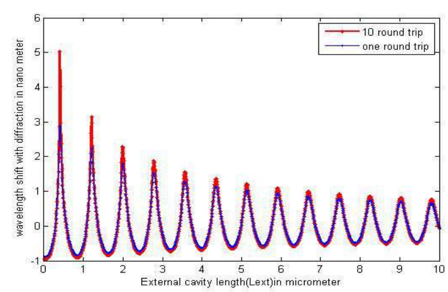

Figure 3: Wavelength shift of an dual external cavity tunable laser as a function of the external mirror position for moderate reflection coefficient first external mirror (0.32).

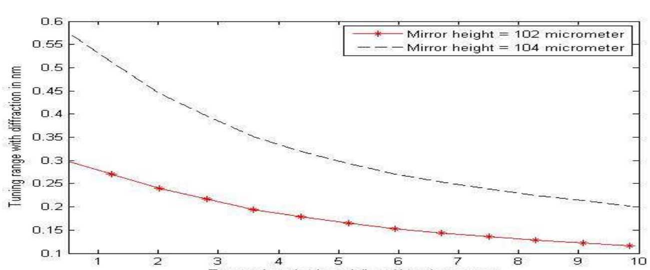

Figure 4: Tuning range of an ECTL as a function of the external mirror position for different flat mirror dimensions h_m, and optical axe height $h = 100$ µm.

one round trip, may still be strong enough to perturb the operation of the laser. A model that accounts for the multiple reflections of the beam in the external cavity is thus developed. This situation is closer to the practical case as usually the mirror is coated by a metal to increase its reflection coefficient. We first examine the effect of multiple reflections on the laser performance when the external mirror reflection is moderate and the obtained results are presented in Figure 3. In case of multiple reflections the amplitude of the beam that coupled back to the laser is increased so the tuning range is increased also. Part of light that reflect from external mirrors is lost due to finite height of mirror as we see in Figure 4.

4. CONCLUSION

In this work we studied the diffraction effects on the single and dual external cavity tunable lasers and calculated the tuning range in both cases by using accurate developed model. The model accounts also multiple reflections in the external cavity tunable laser. The model shows that strong reflection can increase the tuning range. when the beam is truncated due to the finite size of the mirror, the tuning range is decreased. Based on these effects, the external cavity dimensions can be engineered for a required tuning range.

REFERENCES

1. Coldren, L. A., G. A. Fish, Y. Akulova, J. S. Barton, L. Johansson, and C. W. Coldren, "Tunable semiconductor lasers: A tutorial," *Journal of Lightwave Technology*, Vol. 22, No. 1, 193, 2004.
2. Liu, A. Q., *Photonic MEMS Devices Design, Fabrication and Control*, CRC press, 2009.
3. Liu, A. Q. and X. M. Zhang, "A review of MEMS external-cavity tunable lasers," *Journal of Micromechanics and Microengineering*, 2004.
4. Liu, A. Q., X. M. Zhang, D. Y. Tang, and C. Lu, "Tunable laser using micro machined grating with continuous wavelength tuning," 2004.
5. Zhang, X. M., A. Q. Liu, D. Y. Tang, and C. Lu, "Discrete wavelength tunable laser using microelectromechanical systems technology," 2003.
6. Solgaard, O., *Photonic Microsystems: Micro and Nanotechnology Applied to Optical Devices and Systems*, Springer, 2009.
7. Liu, A. Q., X. M. Zhang, V. M. Murukeshan, and Y. L. Lam, "A novel device level micro machined tunable laser using polysilicon 3D mirror," *IEEE Photon. Technol. Lett.*, Vol. 13, 427–429, 2001.
8. Zhu, W. M., W. Zhang, H. Cai, J. Tamil, B. Liu, T. Bourouina, and A. Q. Liu, "AMEMS digital mirror for tunable laser wavelength selection," 2009.
9. Sabry, Y. M., D. Khalil, B. Saadany, and T. Bourouina, "Multi-step etching of three-dimensional sub-millimetre curved silicon microstructures with in-plane principal axis," *Journal of Microelectronic Engineering*, 2013.
10. Sabry, Y. M., B. Saadany, D. Khalil, and T. Bourouina, "Silicon micromirrors with three-dimensional curvature enabling lens-less efficient coupling of free-space light," *Light: Science & Applications, Nature Publishing Group*, Vol. 2, e94, 2013.
11. Zhu, X. and D. T. Cassidy, "Liquid detection with InGaAsP semiconductor lasers having multiple short external cavities," *Applied Optics*, Vol. 35, No. 24, 4689–4693, 1996.
12. Abu-El-Magd, A. M., "Double tuning of a dual external cavity semi conductor laser for broad wavelength tuning with high side mode suppression," Master Thesis, McMaster University, 2005.
13. Fawzy, A. M., S. El-Sabban, I. I. Ismail, and D. Khalil, "On the modeling of an external cavity tunable laser ECTL source with finite mirror dimensions," *PIERS Proceedings*, 691–694, Stockholm, Aug. 12–15, 2013.
14. Voumard, C., R. Salathe, and H. Weber, "Resonance amplifier model describing diode lasers coupled to short external resonators," 1976.
15. Petermann, K., *Laser Diode Modulation and Noise*, Kluwer, London, 1988.
16. Saleh, B. E. A. and M. C. Teich, *Fundamentals of Photonics*, Wiley, 2007.
17. Bandres, M. A. and J. C. Gutiérrez-Vega, "Elliptical beams," *Optical Society of America*, 2008.
18. Marincic, A., "Huygens-Kirchhoff's theory in calculation of elliptical gaussian beam propagation through a lens," *Mikrotalasna Revija*, 2002.

19. Heikkinen, V., J. K. Aikio, T. Alojoki, J. Hiltunen, A.-J. Mattila, J. Ollila, and P. Karioja, "Single-mode tuning of a 1540-nm diode laser using a Fabry-Pérot interferometer," *IEEE Photon. Technol. Lett.*, Vol. 16, 1164–1166, 2004.